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ABSTRACT

Underground nuclear test sites offer an unprecedented opportunity to evaluate processes relevant to high-level waste repository performance in the absence of engineered barriers. Radionuclide migration programs at the Nevada Test Site represent a twenty-five year systematic investigation of the diverse radiologic source terms residual from weapons testing and the evolution of the hydrologic source term which comprises those radionuclides dissolved in or otherwise available for transport by groundwater. The Nevada Test Site shares actinide source terms, correlative geology, an identical tectonic setting, similar climate, and a thick unsaturated zone with the adjacent proposed Yucca Mountain high-level waste repository and provides a natural laboratory to assess long-term radionuclide transport in the near field. Analog studies may ultimately help validate predictions of radionuclide transport from the Yucca Mountain repository.

INTRODUCTION

The underground disposal of high-level nuclear waste poses considerable technical and policy challenges. In this paper high level waste includes radioactive residues from the reprocessing of fuel from nuclear reactors and the production of nuclear weapons in addition to spent fuel elements and targets that have been irradiated in a nuclear reactor. Assessments of how well a repository will contain radionuclides over the long-half lives of the actinides (~ 10^{+3} to 10^{+4} years) which comprise a majority of the radiologic source term will qualify potential sites for the acceptance of this waste. In the United States, Yucca Mountain in southern Nevada is currently being investigated for its suitability to contain more than 70,000 metric tons of high level waste in a mined geologic repository. Before the site can be licensed to accept waste, there must be confidence that the repository will not prematurely release radiation to the environment either through a failure of man-made or natural barriers incorporated in its design. As part of the proposed Yucca Mountain design criteria, a performance assessment must demonstrate that there is a reasonable expectation that for 10,000 years following disposal the reasonably maximally exposed individual receives no more than an annual committed effective dose equivalent of 150 microsieverts (15 mrem) from releases from the undisturbed Yucca Mountain disposal system [1]. While computer models provide a means of predicting and extrapolating the integrity of repository components, including

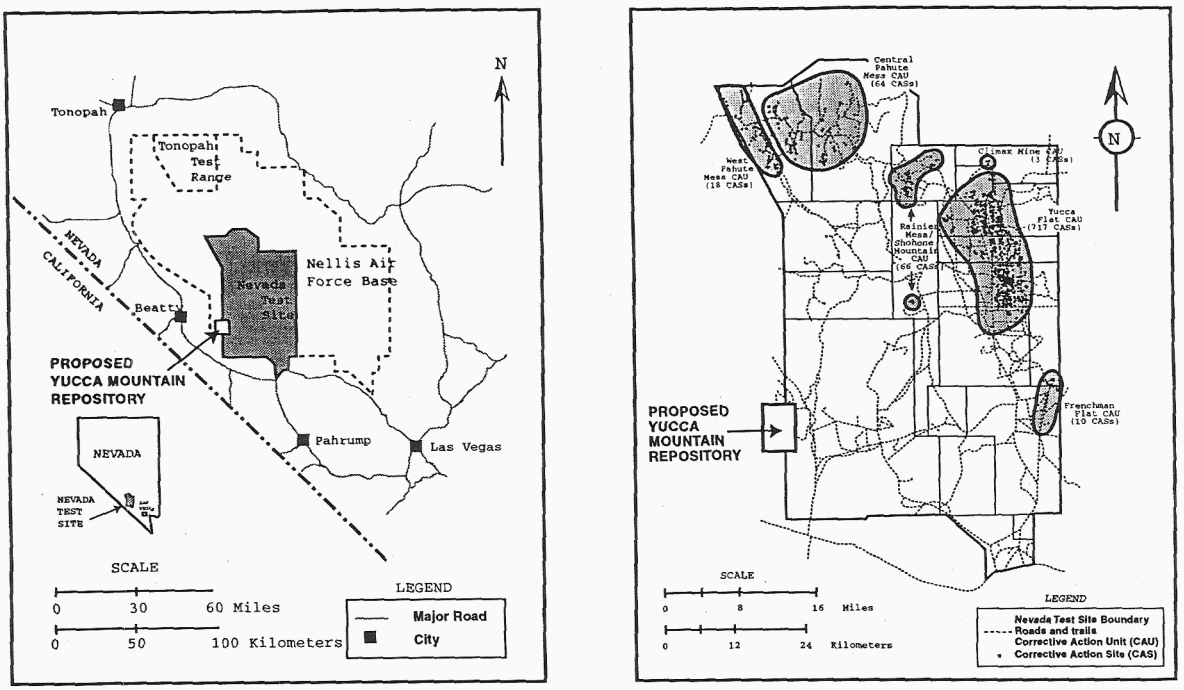
the long-term performance of the geologic and hydrologic setting of the repository, the behavior of constituent materials, thermal loading, radionuclide release, and unsaturated groundwater flow and radionuclide transport, comprehensive validation by numerical means is complex. Although performance assessments rely on repository-specific data to bound realistic estimates of the potential for radionuclide migration, integrated field scale tests are only few in number and limited in both experimental design and duration.

The proposed Yucca Mountain repository adjoins the Nevada Test Site where the United States conducted more than 800 underground nuclear tests from 1951 until the present moratorium on nuclear testing went into effect in September of 1992. Nearly 300 tests were conducted at or below the static water level. The radiologic source term from testing includes all residual radionuclides; the hydrologic source term includes only those radionuclides dissoved in or available for transport by groundwater. Underground nuclear testing has left a residual radiologic source term of tritium, fission products, activation products, and actinides in the zeolitized tuffs identical to those proposed for the adjacent repository. In the one to four decades since the tests were conducted there has been sufficient time for the radiologic source term to be partially converted to the hydrologic source term. While nuclear testing centers at Nevada Test Site have previously been proposed as an analog for the performance of the proposed Yucca Mountain repository [2,3], this paper provides a more comprehensive comparison between the nuclear test experience and high-level nuclear waste disposal at Yucca Mountain.

PROPOSED HIGH LEVEL WASTE DISPOSAL AT YUCCA MOUNTAIN

United States high-level waste is generated by the chemical reprocessing of spent reactor fuel, irradiated targets, and naval propulsion fuel to recover uranium and plutonium. Approximately 10 to 15% of the repository waste will consist of high level waste residues that are a mixture of highly radioactive fission products, traces of uranium and plutonium, and other transuranic elements from the reprocessing of spent fuel [4]. Uranium and plutonium are recovered by reprocessing leaving highly radioactive fission products in an acidic liquid matrix. This waste contains in excess of 99 weight % of the non-volatile fission products produced during reactor operations [5]. Most of the fission products have short half-lives that after 10 years the waste primarily contains ^{90}Sr and ^{137}Cs fission products and small amounts of transuranics. When it is first generated this waste is highly radioactive and occurs as an acidic liquid. To better stabilize this residue for disposal, the liquid or neutralized sludge or salt cake will be immobilized in a silicate glass waste form prior to permanent disposal in a mined geologic repository. The nuclear waste residuals will be mixed with a borosilicate flux, melted, and cast and quenched in corrosion resistant canisters prior to introduction into excavated drifts. Borosilicate glass is a logical choice for a vitreous matrix because of the low melting temperature required to mix the waste with the glass and pour it into waste canisters and because the waste will accommodate a wide variation in waste stream compositions with a capacity for 20 to 30 components. Waste loadings are on the order of 10 to 30 weight percent with the

Figure 1



Index maps showing location of the proposed Yucca Mountain repository (see arrows), the Nevada Test Site (shaded in left), and sites of underground nuclear tests (shaded in right)

radionuclides being dispersed homogeneously throughout the glass [6].

Nearly 90% of the waste at a permanent repository will be spent fuel and not reprocessing waste. Spent fuel consists of solid pellets of uranium oxide enriched in ^{235}U between 3.5 to 4.5 weight percent above natural isotopic composition which are sealed in a cladding of corrosion and heat resistant zirconium alloy and irradiated in a reactor [5]. These tubes are bundled into nuclear fuel assemblies and the fuel is used for 3 to 5 years until the concentration of fission fragments in the fuel element increases to the point where it no longer generates quantities of heat. As the actinide fuel is consumed by fission, the fuel rods and the fuel is removed from the reactor and stored at reactor storage facility where it is allowed to cool and radioactively decay. Eventually the spent fuel will be gathered as uncanistered fuel (spent fuel placed directly in a shipping cask), in dual purpose canisters (containment vessels for the storage and transport of spent fuel) or in disposable canisters (canisters for spent fuel and reprocessing waste with multiple overpacks for storage, transport, and emplacement) for permanent disposal in the repository [7].

The sealed waste packages are to be emplaced in excavated drifts approximately 300 m below ground surface measured from the top of Yucca Mountain. Yucca Mountain consists of an unsaturated sequence of densely welded, highly zeolitized tuffs of Tertiary age that occur in a horizontally bedded and structurally uplifted fault block. The silicic volcanic rocks were erupted between 14 and 11.4 million years ago from calderas which comprise the Southwest Nevada Volcanic Field. The repository horizon is planned for

welded tuffs of the 12.8 million year old Topopah Springs member of the Paintbrush Group. The Paintbrush Group and Topopah Tuff stratigraphically overlie rhyolite tuffs and lavas of the Calico Hills Formation which comprises much of the volcanic section of southern Nevada including the former nuclear testing areas of the Nevada Test Site. The repository horizon is within a ~ 800 m thick unsaturated zone and is sited approximately 240 - 370 m above the water table. Because the mean annual precipitation (from rain and snow) in the vicinity of Yucca Mountain is only approximately 15 cm / year, rapid recharge and infiltration of surface water into the repository is initially expected to be only about 5 mm / year [8]. Potential hydrologic pathways have been identified along a series of northeast-trending fractures and faults which disrupt the volcanic rocks and cause them to dip eastwards. Some fractures and faults are lined by secondary minerals which include zeolites, clays, and calcite. The presence of anthropogenic levels of 'bomb-pulse' ^{36}Cl in an exploratory tunnel bored at the level of the repository horizon may suggest the presence of faster passages between the surface and depth [9].

The groundwater is a dilute Na-HCO_3 type which is characteristic of volcanic aquifers of the Nevada Test Site. Yucca Mountain and the Nevada Test Site are part of a regional groundwater flow system that consists of a regional Paleozoic carbonate aquifer overlain by the Tertiary silicic volcanic section. Water is recharged in basin and range fault bounded mountains more than 300 km north of Yucca Mountain and flows in a southwesterly direction down-gradient towards Yucca Mountain before eventual discharge in the Ash Meadows and the vicinity of Death Valley, California/Nevada [10, 11].

UNDERGROUND NUCLEAR TESTING AT THE NEVADA TEST SITE

The Nevada Test Site has been used by the United States for nuclear testing since 1951. 928 nuclear tests have been conducted there; of these 100 were atmospheric tests. Adequate containment of underground nuclear explosions necessitated conducting the tests at depths of burial between approximately 600 and 1200 m below ground surface. Depth to water at the Nevada Test Site ranges between 210 m in the southeast section to 730 m in the northwest section. The radiologic source term residual from the explosion consists of tritium, fission products, neutron activation products, unburned actinide fuels and fuel residues produced by neutron interactions. Based on both thermodynamic properties and drilling experience into expended nuclear tests, the distribution of radioactivity is reasonably well known. The radioactivity is distributed between the explosion cavity, a fractured exchange zone extending radially away from the cavity to 1.5 times the cavity radius, and a rubble chimney created by broken rock that accumulates as the chimney collapses [12, 13]. Radioactive elements residual from an underground nuclear test are volumetrically incorporated in silicate glass produced by extreme temperatures (> 10^6 °K) and pressures (~ Mbar) associated with the explosion. The glass is produced from 1) the condensation of plasma that forms due to the high temperatures and pressures at the time of explosion, 2) shock melting of rock adjacent to the explosion due to the instantaneous release of energy, and 3) melting of wall rock materials that are outside the molten rind of shocked melted glass that line the first-formed standing detonation cavity [14]. During an underground nuclear explosion nearly 700 metric tons of glass is produced per kiloton of nuclear yield [15]. During their initial condensation,

radionuclides with higher boiling points (alkaline earths, rare earths, high field strength elements, platinum goup elements, and actinides) become incorporated in the molten glass [16].

95 ± 5% of the actinides and long-lived fission products with higher boiling points are volumetrically incorporated in the melt glass that is produced by shock melting accompanying the explosion [17]. Volatile radionuclides with lower boiling points are condense on exposed mineral and fracture surfaces in the exchange zone and rubble chimney. Once radionuclides become incorporated in the glass or on surfaces associated with the nuclear explosive melt debris, there is little subsequent movement of radionuclides by other than hydrologic processes.

Of the 828 underground nuclear tests conducted at the Nevada Test Site nearly 300 were fielded in the saturated zone. Higher yield tests which required deeper containment were conducted in saturated fractured rhyolite and tuff aquifers of Pahute Mesa. In this region hydrologic tests suggest that groundwater may move in velocities up to 76 m/year [18, 19]. In contrast, lower yield nuclear tests were conducted in alluvium and zeolitized tuffs of Yucca and Frenchman Flat which is a closed fault bounded basin underlain by a fractured and regional extensive carbonate aquifer. In these basins vertical groundwater leakage from testing horizons in alluvial and volcanic rock aquifers to the underlying regional carbonate rock aquifers is less than 0.06 m/year [19].

Radionuclide migration from tests conducted in the unsaturated zone incorporates two-phase (fluid and gas) flow and transport. Details regarding transport mechanisms and pathways are known with less certainty because the prevailing assumption is that fluid movement in the unsaturated zone is insufficient to significantly mobilize radionuclides. However, over long periods of time, the connection between the vadose zone and the saturated zone is important because the unsaturated zone tests will serve as long-term point sources for contaminants which may eventually descend and reach the transmissive, regional carbonate aquifer.

COMPARISON OF THE RADIOLOGIC SOURCE TERMS

Within approximately two orders of magnitude the radiologic source terms proposed for the Yucca Mountain high-level waste repository and that residual from the Nevada Test Site are comparable. A total of 70,000 metric tons of waste is proposed to be emplaced the Yucca Mountain repository which includes 63,000 metric tons of commercial nuclear fuel, 2,333 metric tons of defense spent nuclear fuel, and 4,667 metric tons of reprocessing waste residuals [20]. The 70,000 metric tons of waste will be parceled between 10,000 and 11,000 individual waste packages. The inventory for each radioisotope for both the high-level and test source terms has been estimated with accuracy. Spent fuel contains elements with atomic numbers between 1 and 65 and between 81 and 96. After 150 days cooling period, the major fission product contributors of radioactivity from spent fuel from a light water reactor consists of ^{89}Sr, ^{90}Sr, ^{95}Zr, ^{106}Ru, ^{134}Cs, ^{137}Cs, ^{144}Ce, and ^{147}Pm. Remaining spent fuel actinides include ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, ^{241}Cm, and ^{244}Cm [21]. Major radionuclides from reprocessing waste include ^{90}Sr, ^{90}Y, ^{99}Tc, ^{137}Cs, ^{137m}Ba, ^{151}Sm, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, and ^{242}Am [5]. The total curie load for the 70,000 metric tons of waste proposed for the Yucca Mountain repository is approximately 10^8 TBq.

The long-lived fission products and actinides in high-level waste from fuel and reprocessing are nearly identical those residual from nuclear weapons testing. The total radiologic source term for long-lived radionuclides at the Nevada Test Site is estimated to be 10^6 TBq and represents a sum of the individual tests conducted below the water table [22]. The weapons source term is presently dominated by tritium; in a century most of the tritium will have decayed and actinides and fission products will populate the remaining inventory. Both the high-level waste and nuclear weapons source terms will include decay of actinide parents are production of daughter radionuclides including ^{241}Am (from ^{241}Pu), ^{237}Np (from ^{241}Am), ^{231}Pa, ^{230}Th, ^{229}Th, ^{226}Ra, and ^{210}Pb. Activation products produced associated with reactor operations include gases of ^{13}N, ^{16}N, and ^{41}Ar produced by neutron interactions with water molecules and oxygen, nitrogen, and argon dissolved in air. ^{51}Cr, ^{54}Mn, ^{56}Mn, ^{58}Co, ^{60}Co, ^{65}Zn, and ^{59}Fe as condensed activation products [21]. Principal activation products from an underground nuclear test includes ^{10}Be, ^{14}C, ^{22}Na, ^{36}Cl, ^{41}Ca, ^{53}Mn, ^{59}Ni, ^{60}Co, ^{63}Ni, ^{65}Zn, ^{79}Se, ^{81}Kr, ^{93}Mo [22]. The difference in reactor and nuclear test activation products is an artifact of geologic materials, shielding, and diagnostics that are exposed to a neutron flux in the vicinity of an underground nuclear test which are absent in a power reactor.

TRANSPORT OF RADIONUCLIDES AT THE NEVADA TEST SITE

For the long-term isolation of nuclear waste the U.S. will rely on a multi-barrier approach which includes both engineered and natural barriers to radionuclide migration. Repository design combines natural and engineered barriers into a single system. The barriers work in sequence; as the engineered barrier gives way, the geologic barrier will provide containment. The primary mechanism to attenuate radionuclide transport is to minimize the presence of water which potentially interacts with the waste form. The primary function of the barrier system is to keep water away from the waste for as long as possible, to limit the amount of water that eventually may contact the waste, to slow the release of radionuclides from the waste, and to reduce the concentrations of radionuclides in the groundwater [20].

For this reason the repository will be sited ~ 300m above the water table. This setting is similar for nuclear tests conducted in the unsaturated zone. While the setting of unsaturated tests is most analogous to the Yucca Mountain repository, tests conducted below the water table provide a most conservative comparison because the radiologic source term begins nearly immediate conversion to the hydrologic source term. Investigations of the release of radionuclides from the explosion cavity and the behavior of radionuclides in the near-field provide unique insight to processes anticipated to bound the migration of radionuclides at the proposed Yucca Mountain repository.

Radionuclides are released to solution through the dissolution of glass which volumetrically incorporates a majority of the actinides. Glass dissolution is a function of the intrinsic dissolution rate of the glass, the reactive surface area, an affinity term that includes the solubility and concentration products of the reacting fluid, and temperature. Strong compositional gradients occur on exposed and reacting surfaces. Hydration and hydrolysis reactions release alkalis and alkaline earths while creating an advancing gel layer which precedes a layer of secondary mineral precipitates. X-ray diffraction indicates these secondary minerals are smectite clays. pH increases in the fluid due to the

loss of hydrogen into the glass. The resulting alteration layers forms by reaction of the ions released from the glass with the reacting fluid at the solid-fluid interface. The alteration layer may mantle or armor the reactive surface slowing glass reaction. The dissolution of alkali aluminosilicate glass is only moderately sensitive to glass composition over the range from 50 to 75 weight percent SiO_2 at near neutral pH; while basaltic glasses will dissolve faster than silicate glasses, the mechanisms of glass dissolution and alteration products will be similar over this range in silica concentrations [13]. The composition of the major and minor constituents of high-level waste glass (HLW glass) and nuclear melt glass (melt glass) is provided in Table I.

Table I
Compositions of High-Level and Nuclear Melt Glasses

Component	HLW Glass* (weight %)	Melt Glass** (weight %)	Component	HLW Glass (weight %)	Melt Glass** (weight %)
Al_2O_3	3.9	13.7	MgO	2.0	0.9
Am_2O_3	-	$3x10^{-6}$	MnO	1.2	-
B_2O_3	7.3	-	Na_2O	8.7	1.1
CaO	0.6	2.3	NiO	0.1	-
$Ca_3(PO_4)^2$	1.1	-	P_2O_5	-	0.1
Cr_2O_3	0.2	-	PuO_2	-	$4.0x10^{-4}$
Cs_2O	-	$2x10^{-4}$	SiO_2	53.4	75.9
CuO	0.4	-	SrO	-	0.04
Eu_2O_3	-	$1x10^{-4}$	TiO_2	0.3	-
FeO	1.1	-	U_3O_8	0.9	-
Fe_2O_3	11.1	3.1	ZnO	0.1	-
K_2O	2.4	2.9	Other	0.4	-
Li_2O	4.8	-	Total	100.0	

* [5]; proposed chemical composition of HLW glass at Savannah River Site
** [13]
- not determined

Once radionuclides are released from the test debris they will form ionic and molecular species in solution. Studies of sites where nuclear detonations were conducted at or below the static water suggests >98% of the ^3H produced by an underground nuclear test occurs as molecular HTO. Gas, anions, and oxyanions including ^{14}C, ^{36}Cl, ^{85}Kr, ^{99}Tc, ^{129}I are completely dissolved move mutually and conservatively in groundwater. Pumping and static experiments at the sites of saturated nuclear tests indicate these species are diluted, dispersed, and diffused equally in the near field [23, 24, 25]. In contrast, cationic radionuclides, while encountered in the test cavities, will not be as readily transported. Studies in both alluvial and fractured silicic volcanic rocks aquifers at the Nevada Test Site indicate that ^{125}Sb, ^{137}Cs, ^{152}Eu, and ^{154}Eu concentrations in pumped satellite wells are lower by factors of 10^{-2} to 10^{-4} relative to cavity concentrations. These results imply that cationic radionuclides may occur in solution in the cavity but are

attenuated by precipitation or sorption processes that occur over transport distances of ~ 300 meters. Comparative analyses of pumped water samples of a saturated nuclear test cavity taken in 1984 and 1998 indicate that decay-corrected concentrations of ^{3}H and ^{85}Kr decrease due to dispersion while ^{125}Sb, ^{137}Cs, and Eu concentrations increase due to the longer time available for radionuclides to be released from melt glass to solution. Recent flow and contaminant transport modeling of radionuclide migration away from a nuclear test conducted in alluvium substantiate these field observations and suggest that small amounts (between 1 and 5 volume percent) of sorptive minerals including geothite, clinoptilolite, muscovite/illite, and smectite may significantly reduce the mobility of Pu, Sr, and Cs by factors between 50 to 3,200 relative to concentrations in the aqueous phase [13].

In separate studies, the colloidal transport of radionuclides has been demonstrated in fractured volcanic rock aquifers of the Nevada Test Site [26, 27]. ^{3}H, ^{60}Co, ^{137}Cs, ^{152}Eu, ^{154}Eu, ^{155}Eu, and $^{239+240}$ Pu were identified in wells more than 1000m downgradient from nuclear weapon tests. Because the solubility of Eu and Pu is low (i.e, 10^{-8} M for Pu(V) and 10^{-5} M for Eu at near-neutral pH), the water was filtered to determine the relatively higher concentration of these insoluble species. Sequential filtering of the water through 1000 nm, 50nm, and 7nm filters removed more than 95% of the activity for all radionuclides with the exception of tritium which was not affected. The Pu and radionuclide bearing colloids were composed of clays (illite and smectite), zeolites (mordenite and clinoptiloite/heulandite) and cristobalite. These are consistent with minerals which make up a majority of the silicic fractured rock aquifers of the Nevada Test Site. In one case, the source of the Pu was identified through the use of $^{240}Pu/^{239}Pu$ isotope ratios which was identical for unfiltered groundwaters and colloids and uniquely matched the Pu isotope signature of a test conducted 1300 meters upgradient thirty years prior to the water sampling [26]. Despite transport over a kilometer, plutonium concentrations associated with the colloids are ~ 10^{-14} M and do not represent a major flux of actinides from underground testing centers. Unresolved questions include the mechanisms for the plutonium to be released as refractory radionuclides within the cavity environment, whether the plutonium colloids are real (intrinsic) colloids produced through plutonium hydrolysis or are pseudo-colloids formed by sorption of plutonium ions on to ambient groundwater colloids, the extent to which the plutonium sorption onto colloids is a reversible or irreversible process, and the means by which colloids flow through fractures at near ambient groundwater velocities.

INSIGHTS TO REPOSITORY PERFORMANCE

Near-field environments at the Nevada Test Site serve as a natural laboratory to study the processes expected to govern the long-term migration of radionuclides away from Yucca Mountain. As noted above, the two sites share correlative actinide and fission product source terms, volcanic geology, a nearly identical tectonic and structural setting, the same recharge and climate, and a thick unsaturated zone (see Table II). Many nuclear tests are now more than thirty years old and the hydrologic source term has measurable concentrations of actinides and fission products permitting study radionuclide transport in the absence of engineered barriers.

Table II
Comparison of the Proposed Yucca Mountain Repository
and the Nevada Test Site Analog

	Yucca Mountain Repository	Nevada Test Site Analog
Source Term	actinides, fission products	tritium, actinides, fission products
Waste Form	spent fuel, borosilicate glass	high-silica glass
Climate / Precipitation	15 cm / year	< 25 cm / year
Geology	zeolitized welded rhyolite lavas and ash-flow tuffs; fractured	zeolitized rhyolite lavas and tuffs, alluvium, carbonates; fractured
Hydrology	unsaturated; perched water	unsaturated and saturated; dilute HCO_3 groundwater
Controls on Reactive Transport	leaching, precipitation, sorption, colloids	leaching, precipitation, sorption, colloids
Controls on Non-Reactive Transport	dilution, dispersion, diffusion	dilution, dispersion, diffusion

One scenario identified in assessments of repository performance is the percolation of infiltrating seepage water which flows through the unsaturated zone, breaches a waste canister, and carries radionuclides downwards to the saturated zone [28]. The test site analog uses surface water recharging through a rubble chimney to leach radionuclides from the melt glass and rubble in the explosion cavity. Studies of unsaturated zone radionuclide transport emphasize two-phase transport involving fluid solution, concentration, and precipitation and loss of tritium as a gas. Once radionuclides reach the saturated zone research will determine how sorption and precipitation affects the concentration of reactive radionuclides and how diffusion, dispersion, and dilution affects the concentration of non-sorbing species. An optimum test site selected for a repository analog would provide the advantages of being accessible, geologically and hydrologically well characterized, with a known radionuclide source term. The analog site would be drilled at a slant angle to land in the test cavity and the melt glass containing refractory radionuclides. High-sensitivity gamma ray logging will provide information on the in-situ distribution of radioactivity as well as guide the selection of core samples [12]. A second side-track hole drilled below the cavity and completed in the saturated zone will provide information on radionuclide transport below the test as well as be completed as a monitoring well to observe the controls on saturated radionuclide transport. Specific considerations in developing a test site analog to the Yucca Mountain repository would include selection of:

- a nuclear test where the depth of (device) burial is shallow (~ 800m) to minimize drilling costs and recovery of post-shot debris.
- a site where a successful post-shot drill-back provides pre-existing information on the cavity size and the occurrence and distribution of radionuclides in the vicinity of the cavity and collapse chimney.

- a geologic environment similar to that found in the proposed repository block.
- a location where the source and quantity of recharge can be quantified and the geology is well characterized.
- a test where sufficient time has elapsed for radionuclides to be released from and transported away from the cavity under partially saturated and saturated conditions.
- a setting entirely within the unsaturated zone to insure that transport would only involve flow downward to the saturated zone.

Analog test sites have recently been developed at the Nevada Test Site to investigate mechanisms of radionuclide transport relevant to the Yucca Mountain repository. Tunnels bored into tuffs and rhyolites above the water table on Rainier Mesa at the Nevada Test Site have been used for underground nuclear weapons effects tests since 1957. Groundwater recharge from the top of the mesa has created zones of perched water which interact with the radiologic source term through blast induced fractures before discharging from containment barriers and effluent plugs in the tunnels. Water samples taken from three tunnels all contain tritium in excess of the 740 Bq/L drinking water standard in addition to ^{90}Sr, ^{106}Ru, ^{125}Sb, ^{137}Cs, ^{239}Pu, ^{240}Pu, and ^{241}Am. Studies at the Rainier Mesa tunnels are important to understanding the means by which water carries radionuclides through partially saturated fractures in volcanic rocks nearly identical to those of Yucca Mountain.

There are many differences between the nuclear test experience at the Nevada Test Site and the proposed disposal of high-level waste at Yucca Mountain. The Yucca Mountain repository relies on a combination of engineered and natural barriers to isolate waste from the accessible environment. Engineered controls are absent in the context of underground nuclear tests. However the opportunity to observe and measure groundwater flow and radionuclide release, solubility, and transport on a field-scale associated with underground nuclear tests provides increased understanding of natural processes and models important to repository performance. The Nevada Test Site provides a unique opportunity to reduce uncertainties and increase confidence that the Yucca Mountain repository can effectively contain and isolate nuclear waste.

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